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THE HEAT TRANSFER COEFFICIENT

OF A MAGNETIC FLUID

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OF A MAGNETIC FLUID

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PREFACE

The authors became interested in this subject during conversations with Mr. Jacob Rabinow of the National Bureau of Standards, Washington, D.C., who developed and patented the Magnetic Fluid Clutch. During these conversations it was found that no one has determined the thermal conductivity of the type of fluid used in such clutches to the best of the knowledge of the authors. Yet, the heat transfer problem does arise and must be solved for proper future development and use of magnetic fluids in various mechanical devices.

The experimental work of this thesis was performed from January to April at the United States Naval Experiment Station, Annapolis, Md., in the Materials Testing Section where Mr. Robert Plate was most helpful with his many practical suggestions.

The authors wish to express their appreciation for the suggestions and material aid given also by Mr. H. D. Saunderson and Mr. Jacob Rabinow of the National Bureau of Standards, Assistant Professor W. Conley Smith of the U. S. Naval Postgraduate School, and to acknowledge the invaluable aid and guidance of Dr. Gilbert F. Kinney of the U. S. Naval Postgraduate School in the preparation of this thesis.

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CHAPTER I

INTRODUCTION

The interest of the U. S. Navy in the development of a magnetic clutch was the outgrowth of the need for some type of clutch for the servo-mechanisms used in the control of ordnance equipment. Magnetic clutches lend themselves beautifully to such use, because the clutch can be made to engage by remote controls smoothly without any sudden grabbing simply by increasing the magnetic field strength of the coils in the vicinity of the magnetic fluid. This increase in field strength may be made as rapidly or as gradually as desired.

Unfortunately, as in all clutches, there will be some energy loss because of friction which must be dissipated. When the magnetic clutch is de-energized, slippage may be one hundred percent; and when it is fully magnetized, slippage may be reduced to zero by proper design. It is when the clutch is being operated with slippage that friction becomes serious.

Since the energy loss attributed to the friction in the fluid itself and between the fluid and the metallic parts must be dissipated as heat somehow, it must flow either inward into the steel or other material of the shaft or outward through the fluid to the outer casing and then to the air or other cooling medium. This latter path presents the more probable route according to current engineering design theory and practice.

Consequently, to dissipate the frictional energy from within the fluid to some outside cooling agent, it becomes desirable to have some idea of the magnitude of the coefficient of heat transfer for such a magnetic fluid. Until some experimentation is done along this line,

the coefficient may be taken anywhere between the coefficient for oil (.079 BTU.-ft./ft.^{2} hr.^{o}F), and the coefficient for iron (39 BTU.-ft./ft.^{2} hr.^{o}F).McADAMS(1),MARK'S(3). These coefficients become .84 and 468 in units of BTU.-in./ft.^{2} hr.^{o}F. which will be used throughout this thesis. This is a considerable range, and the authors expect to reduce this range to a point where it will be useful as future design data. The only sure way to do this is to conduct the necessary experiments on samples of the actual material.

Another interesting problem to be considered is that the coefficient of heat transfer for this fluid will probably vary depending on whether the fluid is magnetized or not. No one has definitely determined this prior to this investigation.

Therefore, in this thesis work, original experimentation will be conducted on both magnetized and non-magnetized samples of this fluid to determine:

1- The heat transfer coefficient of the non-magnetized magnetic fluid, and

2- Whether or not this coefficient changes with magnetization of the fluid.

Obviously, if original experimentation is to be done, the problem presents two primary considerations, namely

1- The physical laws which the fluid will follow, and

2- The actual laboratory equipment and procedure to be used to demonstrate these laws.

Fortunately, early in the search for equipment, an installation for the investigation of heat transfer through insulating materials was located at the Engineering Experiment Station, Annapolis, Md.

This equipment was made available through the kindness of Captain L. W. Ceighton, U. S. Navy, Assistant Director of Services, and Mr. Robert Plate of the Materials Testing Section, Engineering Experiment Station. It was, of course, necessary to modify this equipment to meet the special requirements for this experiment.

CHAPTER II

PRACTICAL CONSIDERATIONS

The first problem in modifying the available equipment at the Engineering Experiment Station was to design and fabricate suitable containers for the fluid during the tests. After conducting preliminary experiments in mixing the iron and oil so that it would not separate appreciably by gravitational force, it became apparent that heat transfer by convection would be unimportant compared to that by conduction and could safely be neglected. The viscosity of the oil alone at 125°F was 60 SSU(Saybolt Seconds Universal) which is comparable to that of the Navy General Purpose Lubricating Oil (symbol 2075) which is a little lighter than an SAE 10 lubricating oil. Likewise, the viscosity of the iron and oil mixture at 76°F was 137.3 KU (Kreb Units) which is comparable to a thick lead paint or a soft butter. Consequently, containers 4" x 4" x 1" were designed and made of lucite and copper. Two containers were to be used and were to fit snugly against the hot plate element of the equipment which had 4" x 4" hot surfaces with a guard ring extending out from these plate dimensions 2" on each side. For illustrations of these containers see Figures 1 and 2, pages 38 and 39. The copper plates of the containers fit against similar plates attached to the hot and cold elements in the heating box, and these plates had thermocouple wires soldered to their centers via milled slots leading in from the edges. The copper plates were used for their extremely high heat conductivity which would introduce a minimum of error into the calculations. The lucite spacer strips used as sides for the containers were used for their very low heat conductivity and for their ease of fabri-

cation. The lucite and copper were bonded together with "Pliobond", manufactured by Goodyear Tire and Rubber Company, and all joints were then coated with liquid "Experimental Lacquer X-124, Formulation RS-60-20" (Saran Coating), manufactured by Dow Chemical Company, to insure tightness of the joints.

The next major problem was to design and fabricate some means of producing a magnetizing flux which would fit into the existing heating box, which would be sufficiently powerful to do the job required, and which could be varied in strength and easily controlled. Since a symetrical field was desired, the final design consisted of two laminated iron cored coils of 800 turns each using #16 copper wire. These coils would fit snugly into the box using a 4" x 4" square cross section for the cores (see Fig. 3,page 40). These then could be aligned axially with the fluid containers. Flux measurements were made using these coils and a Type -TS-15A/AP Fluxmeter # 3790, manufactured by Marion Electrical Instrument Company, Manchester, N. H. These measurements are recorded on page 25 and indicated that these coils would serve the purpose satisfactorily using a direct current supply.

Sufficient direct current power was not available in the laboratory; so a 440 volt 3 phase motor was used to drive a compound wound direct current generator. Unfortunately, it was found that the fluctuations in the direct current as generated caused sufficient variations in the magnetic flux in and around the fluid under test to produce an emf in the thermocouple wires considerably greater than that produced by the temperature differences in the thermocouples themselves. This complication led to the design and construction of a thyratron controlled voltage regulator, but the regulator proved

inadequate for the job it was to handle; so finally a battery source of d.c. power was obtained. The generator was used during the warm-up periods and preliminary adjustments, but all final adjustments were made and readings taken using only battery power. This system worked perfectly, and no further trouble was experienced from this source.

However, another complication arose from the energy dissipated as heat by the field coils. The outside surface temperature of the coils with 3.7 amperes of field current was above 200°F, and with the heating box closed, the guard ring was unable to prevent heat gains into the magnetic fluid through the insulation since the ambient temperature in the box was around 150°F. This necessitated opening the side covers of the box to help dissipate some of this heat to the room. Unfortunately, due to weather conditions and other tests being conducted in the room, the room temperature varied throughout the day and made it difficult to maintain a zero heat balance through the guard ring for as long a time as was desired. Nevertheless, by careful adjustment and many attempts, sufficient points were obtained with a zero balance to realize the objective of this thesis, i.e., to obtain the heat transfer coefficient of a magnetic fluid and to establish the amount and manner of variation of this coefficient when the fluid is magnetized.

The adaptation of the available equipment to the requirements of this investigation was a difficult and time consuming job since so little was known of the behavior of the equipment in the ranges to be used. As a result of these difficulties and the delicate balance required, time did not permit the authors to make as many check runs

as originally contemplated. The limited range of the equipment available did not allow as great a temperature range to be covered as was originally planned. Nevertheless, the results obtained are both accurate and reproducible.. One complete check run was made using a fresh mixture of the same proportions as the first mixture, and the results obtained were in excellent agreement with earlier results. Consequently the authors feel that the information obtained by this study will be of definite value to future design studies where magnetic fluids of this type are used.

For a general picture of the equipment and layout, see Fig. 4, page 41, and for the diagrams of the electrical circuits, see Figs. 5 and 6, pages 32 and 33.

CHAPTER III

THEORETICAL CONSIDERATIONS

The fundamental law of heat transfer by conduction has been formulated by Fourier and has been so well substantiated by so many competent observers that it will be accepted as proven. This law states that the instantaneous rate of heat flow through a substance is equal to the product of three factors; the area (A) of the cross section at right angles to the direction of heat flow, the temperature gradient $\left(\frac{dt}{dx}\right)$ in the direction of heat flow, and a proportionality factor (k) known as the thermal conductivity of the substance. Mathematically the law may be stated as follows:

$$dQ/d\theta = -kA\ dt/dx$$

where dQ is the amount of heat flowing during the time $d\theta$, dt/dx is the rate of change of temperature with position (or thermal gradient), and the negative sign is used to show that heat flows from the region of higher temperature to the lower temperature region. McAdams (1).

If the rate of flow of heat is held constant and the rate of change of temperature with time is zero, the equation reduces to

$$q = -kA\ dt/dx$$

If the total temperature difference is small the thermal conductivity k may be considered constant and the equation may be integrated to give

$$q \int_0^L dx = -kA \int_{t_0}^{t_1} dt$$

$$q L = -kA \Delta t$$

$$k = -qL/A\Delta t$$

where L is the total length of the path and Δt is the difference between high and low temperatures.

All the quantities on the right side of the equation are measureable and thus k may be determined.

For a non-homogeneous fluid having a random distribution of particles such as is under consideration in the present case it seems reasonable to suppose that the value of k determined by experiment will fall somewhere between .079 the accepted value for oil and 39 the accepted value for iron. McAdams(1). For example, assuming a fluid of 6.93 parts iron to 1 part oil by weight, it seems reasonable to assume that the measured k for this fluid would be somewhat less than the overall k for this ratio of iron and oil in parallel paths and greater than the same ratio in a series path. Calculating the overall k for a series path:

IF $$R = \frac{L}{kA}$$

THEN $$R_T = \frac{\Delta t_T}{q_T}, \quad R_1 = \frac{\Delta t_1}{q_1}, \quad R_2 = \frac{\Delta t_2}{q_2}$$

AND $$\Delta t_1 = q_1 R_1, \quad \Delta t_2 = q_2 R_2$$

THUS $$\Delta t_1 + \Delta t_2 = q_1 R_1 + q_2 R_2$$

BUT FOR A SERIES PATH $$\Delta t_1 + \Delta t_2 = \Delta t_T$$

AND $$q_1 = q_2 = q_T$$

SO $$\Delta t_T = q_T (R_1 + R_2)$$

OR $$\frac{\Delta t_T}{q_T} = R_1 + R_2$$

BUT SINCE $\frac{\Delta t_T}{q_T} = R_T$

THEREFORE $R_T = R_1 + R_2$

THUS $\frac{L_T}{k_T A_T} = \frac{L_1}{k_1 A_1} + \frac{L_2}{k_2 A_2}$

BUT, FOR A SERIES PATH $A_T = A_1 = A_2$

THEREFORE $\frac{L_T}{k_T} = \frac{L_1}{k_1} + \frac{L_2}{k_2}$

FOR THIS MIXTURE $\frac{1.00}{6.93}\left(\begin{matrix}\text{WEIGHT}\\ \text{RATIO}\end{matrix}\right) \times \frac{7.87\,(\rho\ \text{IRON})}{.8486\,(\rho\ \text{OIL})} = \frac{1.345}{1.000}\left(\begin{matrix}\text{VOLUME}\\ \text{RATIO}\end{matrix}\right)$

THEN $L_1 = \frac{1.345}{1+1.345} = .574$

AND $L_2 = 1 - L_1 = 1 - .574 = .426$

AND IF $k_1 = .079$ AND $k_2 = 39.0$

THEN $\frac{1.0}{k_T} = \frac{.574}{.079} + \frac{.426}{39.0}$

THEREFORE $k_T = .1375$ BTU-FT/HR FT^2 °F

OR $k_T = .1375 \times 12\left(\frac{IN}{FT}\right) = 1.65$ BTU-IN/HR FT^2 °F

For parallel paths:

$q_1 + q_2 = q_T$, $L_1 = L_2 = L_T$, AND $\Delta t_1 = \Delta t_2 = \Delta t_T$

THUS $q_1 + q_2 = \frac{k_1 A_1 \Delta t_1}{L_1} + \frac{k_2 A_2 \Delta t_2}{L_2} = \frac{k_T A_T \Delta t_T}{L_T}$

SO $k_1 A_1 + k_2 A_2 = k_T A_T$

FOR THIS MIXTURE $A_1 = .574$, $A_2 = .426$, $k_1 = .079$, $k_2 = 39.0$

THEN $.574 \times .079 + .426 \times 39.0 = k_T \times 1$

THUS $.045 + 16.616 = k_T$

OR $k_T = 16.661$ BTU-FT/HR FT^2 °F

OR $k_T = 16.661 \times 12\left(\frac{IN}{FT}\right) = 199.93$ BTU-IN/HR FT^2 °F

The tendency of iron filings to align themselves in a magnetic field so as to minimize the reluctance of the field is a physical phenomenon that has been observed for centuries and is universally accepted. This tendency will, in this case, result in a situation approaching parallel paths. As the field becomes stronger the forces causing the particles to become continuous lines get greater and the fluid approaches a series of parallel paths more closely. After the filings become fully aligned any further increase in field strength should have no effect on the conductivity. As the mean temperature of the fluid increases the oil becomes less viscous and there is less resistance to the movement of the iron particles. This should result in a positive slope in the temperature versus conductivity curve for constant field strength. Higher mean temperatures will also result in a greater ratio of iron volume to oil volume as the coefficient of thermal expansion of iron is greater than that of oil. This will also result in an increase in conductivity with temperature. The magnetostriction effect of the field on the iron will result in an increase in the volume of the iron. Loeb(2). This effect should result in an increase in conductivity with field strength for constant temperature.

Theoretical sources of error in the experimental set-up used include the following:

1. Heat leakage in a lateral direction.
2. Entrapped air.
3. Heat transfer through the Lucite sides of the boxes.
4. Heat transfer by convection.
5. Heat transfer by radiation.
6. Temperature drop through the copper plates.
7. Film effects.

In conducting the experiment the following assumptions regarding the above sources of error were made:

a) That heat losses through the edges of the hot plate are negligible and that all energy supplied to the hot plate is transferred to the fluid. This assumption is justified because a guard ring surrounded the hot plate and four differential couples were arranged to measure any lateral temperature difference. Readings were taken when these couples indicated no lateral heat flow. It was also assumed that there was no heat flow from the fluid to the room. This assumption is justified because the sides of the containers were made of lucite and insulated with two inches of fibre glass.

b) The containers were completely filled with fluid, allowed to stand over night, and a vent hole was left in the top of each container; so it is felt that there was no appreciable amount of entrapped air present.

c) No correction has been made for such heat as is certain to have been transferred through the edges of the boxes. The area of these edges was small compared to the area of the fluid and the conductivity of lucite is low(1.44 Btu-in./hr ft.^{2} deg.F.). SASSO(5).

d) The viscosity of the fluid was so great and the temperature differences so small that it was assumed no heat was transferred by convection.

e) The low mean temperature, small temperature differences, and shielding effect of the fluid were considered sufficient to justify the assumption that there was no appreciable heat transfer

by radiation.

f) It was assumed that the temperature drop through the copper was negligible as the copper plates were thin(.0655 in.) and the conductivity of copper is so high($2664 \frac{BTU-IN}{HR\ FT^2\ {}^\circ F}$)Marks(3).

g) There was no allowance made for any film effect. It is felt that the use of a wetting agent and the high viscosity of the fluid would be enough to minimize film formation.

h) It was assumed that the direction of the magnetic field was parallel to the direction of heat flow. The field was assumed to be uniform and symetrically located with respect to the magnetic fluid. These assumptions are justified by the fact that the coils were carefully located, and the iron cores were of the same cross sectional area as the fluid containers.

CHAPTER IV

PROCEDURE

The procedure followed in getting the data required for this investigation was designed to ensure accuracy and yet save as much time as possible. The equipment was started in the morning using the motor generator as a source of exciting current for the field. After the equipment had been running for about three hours and had arrived at a steady state condition, exitation was shifted to batteries and the guard ring current was varied until a reading of less than .2 on the most sensitive scale of the galvanometer was obtained for the four differential couples in series. Readings were then taken on the hot and cold side thermocouples and the heating coil current. The potentiometer was adjusted by means of the standard cell before each set of readings and checked again after the readings were completed. Great care was taken to maintain the cold junctions in a bath of crushed ice. By this frequent checking of the potentiometer and accurate control of the cold junction temperature it was assured that readings taken contained no errors due to the measuring instruments.

Energy flowing into the fluid was determined by measuring the wattage supplied to the heating coil. All this energy was assumed to flow through the fluid due to the balancing effect of the guard ring. Δt was determined by the hot and cold side thermocouples.

At the higher rates of field current it was necessary to remove the covers from the box to prevent the ambient temperature from getting too high. This resulted in fluctuations of ambient temperature due to such things as open windows, etc., which made it very difficult to

maintain a balance across the differential couples. As a result, fewer points were obtained than anticipated. However, it is felt that a few accurate points are better than many points of doubtful accuracy.

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CHAPTER V

RESULTS AND CONCLUSIONS

The results obtained by this experiment were as conclusive as the limitations of time and equipment would permit. It is felt that the range of temperature obtainable was too small to justify any broad statements and that the field strengths used were too low to show any possible effects of saturation since saturation was never reached. Nevertheless, the results do show that the effects predicted by the theoretical considerations were actually present and were demonstrated beyond any doubt.

The curves of "Conductivity versus Mean Temperature for Constant Field Strengths" (Figure 9, page 36) definitely show an increase in heat transfer with field strength that can not be explained by experimental inaccuracy. The positive slope of this curve for higher field strength tends to illustrate the effect of viscosity on the resistance to movement of the iron particles. As the oil heated up, its viscosity decreased and the movement of the particles increased. It is not possible to separate the magnetostriction effects from the other effects of the magnetic field.

The temperature range permissible by the equipment was not great enough to demonstrate the effect of thermal expansion on the conductivity. This effect should result in a slope of the "No Field" curve, but no appreciable slope was apparent.

The agreement found between results obtained with the two separate batches of fluid was good and indicated that the results are reproducible.

The values obtained for the coefficient of heat transfer were

within the range anticipated and are a definite contribution to available design data. It is felt that the field strengths obtainable with the equipment were suffiuient to give an indication of a trend but not sufficient to give limiting values for the heat transfer coefficient which should occur when the magnetic fluid is in a saturated field (see Fig. 10, page 37). It is thought that the effect of the field will increase as the strength of the field increases up to saturation; so the curve of thermal conductivity versus field strength will not be linear. Certainly as saturation is approached the curve will level off.

In conclusion, as a result of this research, a value of 4.8 BTU -in/Hr.Ft^2 $^\circ$F is submitted as a conservative figure for design purposes under "No Field" conditions. In general, while lower than the actual value that would be encountered under strong magnetic or saturated conditions, a value of 5.0 BTU-in/Hr.Ft^2 $^\circ$F will give a conservative design where it is desired to take into consideration the effects of magnetic field strengths without having to grossly overdesign the equipment.

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APPENDIX

a) <u>Calibration of Equipment:</u>

The accuracy of any data is limited to the accuracy of the equipment and to the ability of the operators to use the equipment properly. In order to reduce the possibility of errors, the equipment was designed as simply as possible to still do the job. One reason for choosing a one inch length of fluid path for the test was to reduce the percentage value of any errors which might arise from micrometer measurements of lengths.

In spite of detailed instruction by the personnel of the Materials Testing Section, the usual mistakes of inexperience were made, but these became apparent either while in the process of taking readings or during computations based on faulty readings. After considerable practice, experience was gained. With experience, the help of expert supervision, and by constant checking between operators, errors in the use of the equipment were eliminated.

The accuracy of the equipment was frequently checked against the accepted standards used at the Engineering Experiment Station. A standard cell was checked by the Instrument Section and issued for use in checking the potentiometer. The potentiometer was checked against this standard before and after each set of readings, and if any discrepancy appeared, the readings were discarded. Means were available to zeroize the galvanometer; so no correction for it was necessary in the computations.

The readings of the potentiometer were accurate to four decimal places with easy interpolation to a fifth place. These readings were used to enter a series of curves which were drawn from the Conversion

Tables given on page 21 to give compatible accuracy. A less accurate curve which covers the whole range of temperatures is enclosed as Figure 7 on page 34 to illustrate the technique.

Initial calculations were made by longhand, and all final calculations were made using a computing machine.

CONVERSION TABLES FOR

COPPER VS CONSTANTAN THERMOCOUPLES WITH

REFERENCE JUNCTION 32° F.

DEGREES	MILLIVOLTS	DEGREES	MILLIVOLTS
50 F	.390	78 F	1.012
52	.434	80	1.057
54	.478	82	1.103
56	.522	84	1.148
58	.566	86	1.194
60	.610	88	1.239
62	.654	90	1.285
64	.699	92	1.331
66	.743	94	1.377
68	.788	96	1.424
70	.832	98	1.470
72	.877	100	1.516
74	.922		
76	.967		

From: "Standard Conversion Tables for L&N Thermocouples" (STD 11031-A)

Published by: Leeds & Northrup Co.
Philadelphia, Pa.

b) Sample Calculations:

(Basic Equation) $Q = \frac{K \times A \times \Delta T}{L}$

Or, $K = \frac{Q \times L}{A \times \Delta T}$, where

Q = Total Heat Input per hour = $I^2 \times R$ = Watts

L = Length of magnetic fluid path = Inches

A = Cross-sectional Area of fluid = $(\text{Inches})^2$

ΔT = Temperature difference between hotside and coldside = $^{\circ}F$

In this experiment with the hotplate in the center and heat flowing from it in two directions, the above Total Q must be divided by two for unidirectional flow which is desired.

Then, $K = \frac{I^2R(\text{watts}) \times L\ (\text{inches})}{2 \times A(\text{inches})^2 \times \Delta T(^{\circ}F)}$, and in this

I = Measured for each reading in amperes

R = 6.42 ohms, corrected resistance for hot plate

L = Measured for each run in inches

A = $4'' \times 4''$ = 16 inches^2 = $\frac{16}{144}$ = 1/9 ft^2

ΔT = Measured for each reading in $^{\circ}F$

To convert: Multiply watts by 3.415 to obtain $\frac{BTU}{hour}$

Or, $K = \frac{I^2 \times 6.42 \times L \times 3.415}{\Delta T \times 2 \times 1/9}$; Data from Run # 1: First readings

$L = 1.013$

$I = .8763$

$\Delta T = 15.68$

$= \frac{98.659\ I^2\ L}{\Delta T}$

Therefore, $K = \frac{99.96 \times .8763^2}{15.68} = 4.895\ \frac{BTU - in}{Hr.\ Ft^2\ ^{\circ}F}$

$4.895\ \frac{BTU - in}{Hr.\ Ft^2\ ^{\circ}F}$

c) Miscellaneous Data:

(1) Materials used in the Magnetic Fluid were-

1- Carbonyl Iron Powder E, experimental lot with fines removed, supplied by General Aniline Works.

2- White mineral oil, U.S.P. Light, manufactured by Surgeons Products Inc., Baltimore, Md.

(2) Mixture of Iron and Oil - Weight of Oil = 300 grams
Weight of Iron = 2080 grams

Ratio, by weight $= \frac{2080}{300} = 6.93$ to 1.

Note: To oil was added 4 drops of polyethylene glycol oleate as a wetting agent.

(3) Viscosity Test of Oil -

Instrument Used: Viscometer, Electric Temperature Control, #210, manufactured by Scientific Instrument Co.

Method Used: Federal Standard Stock Catalog VV-L-791b, Method 30.44 (ASTM D88-38).

Results:	Run # 1 -	59.8 seconds	at oil temp. of 125°F
	Run # 2 -	60.6	"
	Run # 3 -	60.2	"
	Average -	60.2 S.S.U.	at oil temp. of 125°F

(4) Viscosity of Mixture -

Instrument used: Stormer Viscosimeter # 4414, manufactured by Arthur H. Thomas Co., Philadelphia, Pa.

Method used: Federal Standard Stock Catalog TT-P-141a, Method 428.1

Results:	Run # 1 with 950 grams	-	29.3 seconds
	Run # 2 " " "	-	29.25 "
	Run # 3 " 975 "	-	28.2 "
	Run # 4 " 925 "	-	30.3 "

For this data, from Table, Viscosity = 137.3 K.U.

For this data, see also Figure 8, page 35

Note: Temperature of mixture during viscosity test = 76°F.

(5) Specific Gravity of Oil -

Weight of beaker and 60 cc sample -	89.2990 grams
Weight of beaker alone - - - - - - - -	38.3826 "
Weight of 60 cc sample alone - - - -	50.9164 "

Therefore, 1 cc $= \frac{50.9164}{60} = .8486$ grams

Thus, Density $= \frac{.8486 \times 2.205 \times 10^{-3} (\text{lbs})}{6.102 \times 10^{-5} (\text{inches})^3} = .03066 \frac{\text{lbs}}{\text{in}^3}$

$= 52.9 \frac{\text{lbs}}{\text{ft}^3}$ (See Eshbach, p.1-135 to 1-137)

Specific Gravity $= \frac{52.9}{62.4} = .848$

(6) Thickness measurements for length of fluid path -

(For Runs # 1 & # 2)	Top Front	Top Rear	Bottom Front	Bottom Rear
Peg to peg, assembled -	5.245	5.247	5.184	5.138
No container in posit.	2.945	2.971	2.884	2.860
Container and Fluid - -	2.300	2.276	2.300	2.278
Thickness of Containers	.262	.262	.262	.262
Length of Fluid Path - in two directions	2.038	2.014	2.038	2.016

Average length fluid path in one direction = 1.013 inches.

(For Runs # 3 & # 4)	Top Front	Top Rear	Bottom Front	Bottom Rear
Peg to peg, assembled -	5.182	5.213	5.136	5.121
No container in posit.-	2.936	2.963	2.865	2.856
Container and Fluid - -	2.246	2.250	2.271	2.265
Thickness of Containers	.262	.262	.262	.262
Length of Fluid Path - in two directions	1.984	1.988	2.009	2.003

Average length fluid path in one direction = .998 inches.

(For Runs #5, #6, #7, & #8)	Top Front	Top Rear	Bottom Front	Bottom Rear
Peg to peg, assembled -	5.184	5.227	5.136	5.129
No container in posit.-	2.936	2.963	2.865	2.856
Container & Fluid - - -	2.248	2.264	2.271	2.273
Thickness of containers	.262	.262	.262	.262
Length of fluid path - in two directions	1.986	2.002	2.009	2.011

Average length fluid path in one direction = 1.001 inches

(7) Flux measurements and calculations -

Ampere-turns	Lines/sq.inch	Distance between pole faces:
12890	7750	3.25"
14080	8260	3.25"
15680	8890	3.25"
13800	7750	3.50"
14550	8120	3.50"
14250	7100? (extrapolated)	3.75"

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Run	Date	Time	Cool. [illegible]	Amb. Box	[illegible] Th.6.41	[illegible] T.6.42	[illegible] Th.6.63	[illegible]	[illegible] Eq.6.49
Run #1	2/1	1420	48.9	70.7	.07628	.07656	.04010	.04255	-.5
	2/1	1430	48.9	71.0	.07625	.07660	.04014	.04263	-.8
	2/1	1605	48.9	70.0	.07646	.07600	.03990	.04240	-.6
	2/1	1625	48.9	70.0	.07640	.07600	.03998	.04245	-.5
Run #2	2/2	1425	48.8	71.4	.11265	.11260	.04220	.04750	0
	2/2	1500	48.8	71.8	.11250	.11250	.04250	.04760	.08
	2/2	1515	48.8	71.8	.11250	.11250	.04250	.04750	0
	2/2	1530	48.8	71.8	.11250	.11250	.04250	.04730	-.1
	2/2	1600	48.8	71.9	.11260	.11256	.04250	.04760	.1
Run #3	3/22	1452	49.8	box open	.11340	.11500	.05000	.05350	0
	3/22	1530	49.8	"	.114[illegible]	.11580	.05010	.05370	0

Run	Date	Time	Ave Temp Hotside	Ave Temp Coldside	Ave Temp Difference	Ave Temp (Mean)	Heat Coil (Amperes)	Amp. Turns	Coef. "K"
Run #1	2/1	1420	66.98	51.30	15.68	59.14	.8763	0	4.90
	2/1	1430	66.95	51.08	15.87	59.02	.8700	0	4.77
	2/1	1605	66.90	51.00	15.90	58.95	.8748	0	4.81
	2/1	1625	66.85	51.05	15.80	58.95	.8757	0	4.85
Run #2	2/2	1423	83.05	52.70	30.35	67.88	1.2085	0	4.81
	2/2	1500	82.97	52.77	30.20	67.87	1.2080	0	4.83
	2/2	1515	82.97	52.75	30.22	67.86	1.2080	0	4.83
	2/2	1530	82.98	52.77	30.21	67.88	1.2079	0	4.83
	2/2	1600	83.02	52.75	30.27	67.89	1.2073	0	4.82
Run #3	3/22	1452	84.02	55.89	28.13	69.96	1.2594	6320	5.55
	3/22	1530	83.73	55.80	27.93	69.77	1.2564	6320	5.57

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	Date	Time	Cool. Wtr.	Amb. Box T.	Hotside Th.C.#1	Hotside Th.C.#2	Coldside Th.C.#3	Coldside Th.C.#4	Guardring Th.C.#9
Run #4	3/25	1430	48.9	89.0	.06573	.06580	.03842	.03962	0
	3/25	1440	48.9	89.5	.06621	.06621	.03795	.03948	0
	3/25	1600	48.9	89.0	.06590	.06610	.03815	.03975	0
	3/25	1610	48.9	88.6	.06605	.06615	.03800	.03945	0
Run #5	3/31	1450	48.9	91.0	.06918	.06940	.03907	.03862	0
	3/31	1540	48.9	91.5	.06840	.06850	.03895	.03875	0
	3/31	1600	48.9	92.2	.06800	.06820	.03900	.03865	0
Run #6	4/4	1542	48.9	box open	.10106	.10215	.04607	.04585	0
	4/4	1547	48.9	"	.10173	.10265	.04610	.04583	0
	4/4	1600	48.9	"	.10255	.10323	.04605	.04575	0

	Date	Time	Ave Temp Hotside	Ave Temp Coldside	Ave Temp Difference	Ave Temp (Mean)	Heat Coil (Amperes)	Amp. Turns	Coef. "K"
Run 54	3/25	1430	62.17	49.85	12.32	56.01	.8305	6400	5.51
	3/25	1440	62.37	49.80	12.57	56.09	.8300	6400	5.40
	3/25	1600	62.27	50.00	12.27	56.14	.8213	6400	5.41
	3/25	1610	62.32	49.88	12.44	56.10	.8214	6400	5.34
Run 55	3/31	1450	63.75	49.90	13.85	56.83	.8192	0	4.79
	3/31	1540	63.37	49.90	13.47	56.64	.8058	0	4.76
	3/31	[illegible]	[illegible].20	49.90	13.5[illegible]	56.[illegible]	.8092	0	4.83
	4/4	[illegible]	[illegible].24	52.15	25.09	65.70	1.1[illegible]	4816	5.37
	4/4	[illegible]	[illegible].41	53.16	25.29	65.61	1.1[illegible]	4816	5.37
	4/4	[illegible]	78.75	53.14	25.61	65.[illegible]	1.[illegible]	4816	5.36

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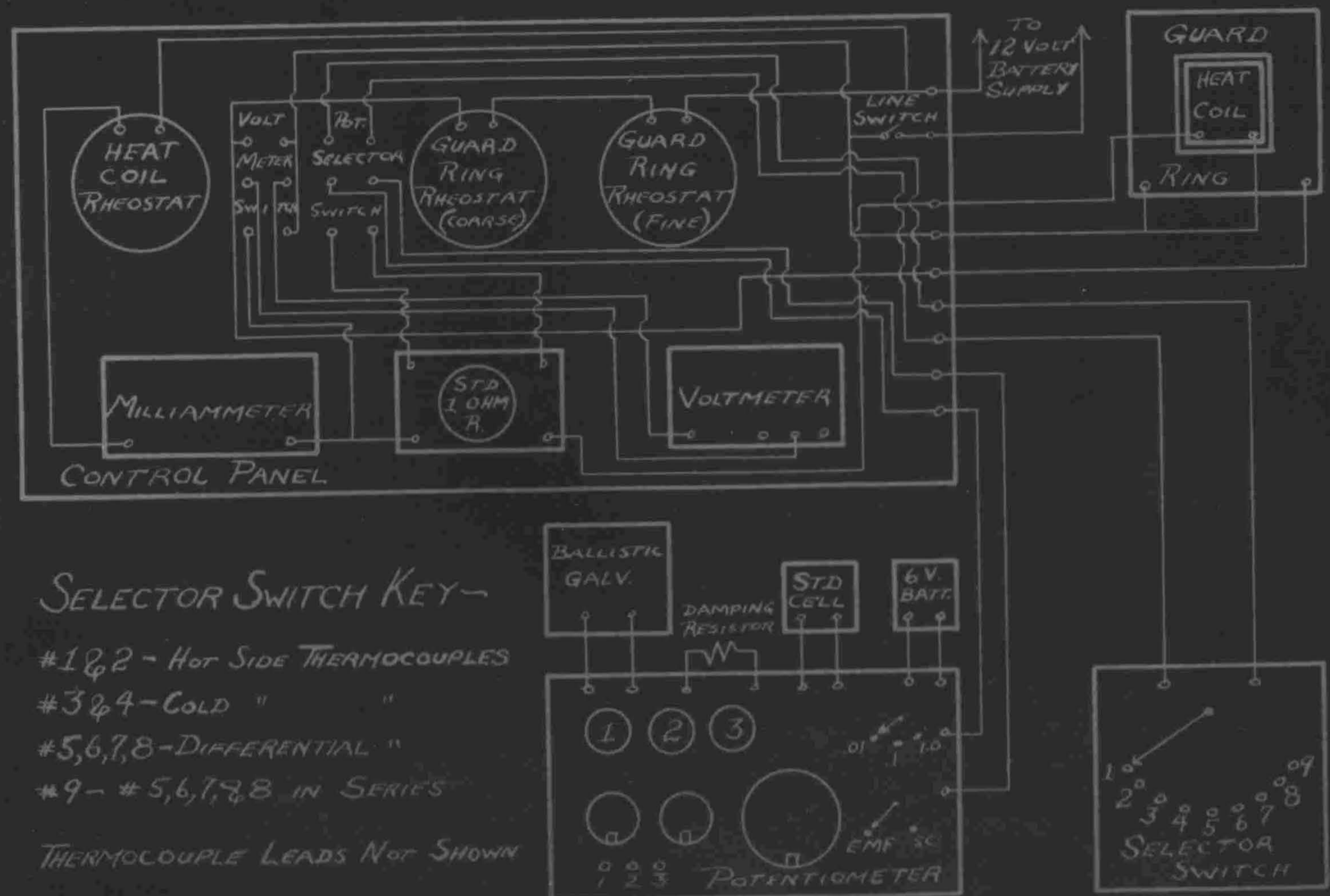
	Date	Time	Cool. Wtr.	Amb. Box T.	Hotside Th.C.#1	Hotside Th.C.#2	Coldside Th.C.#3	Coldside Th.C.#4	Guardring Th.C.#9
Run #7	4/5	1200	49.8	box open	.09970	.10000	.04520	.04520	0
Run #7	4/5	1300	49.8	"	.10140	.10190	.04600	.04570	0
Run #7	4/5	1400	49.8	"	.10140	.10190	.04535	.04550	0
Run #8	4/8	1300	49.8	"	.11473	.11663.	.04839	.04967	0
Run #8	4/8	1400	49.8	"	.11640	.11789	.04650	.04810	0

NOTE: K for Runs #1 & #2 = $\frac{99.96\ I^2}{\Delta T}$

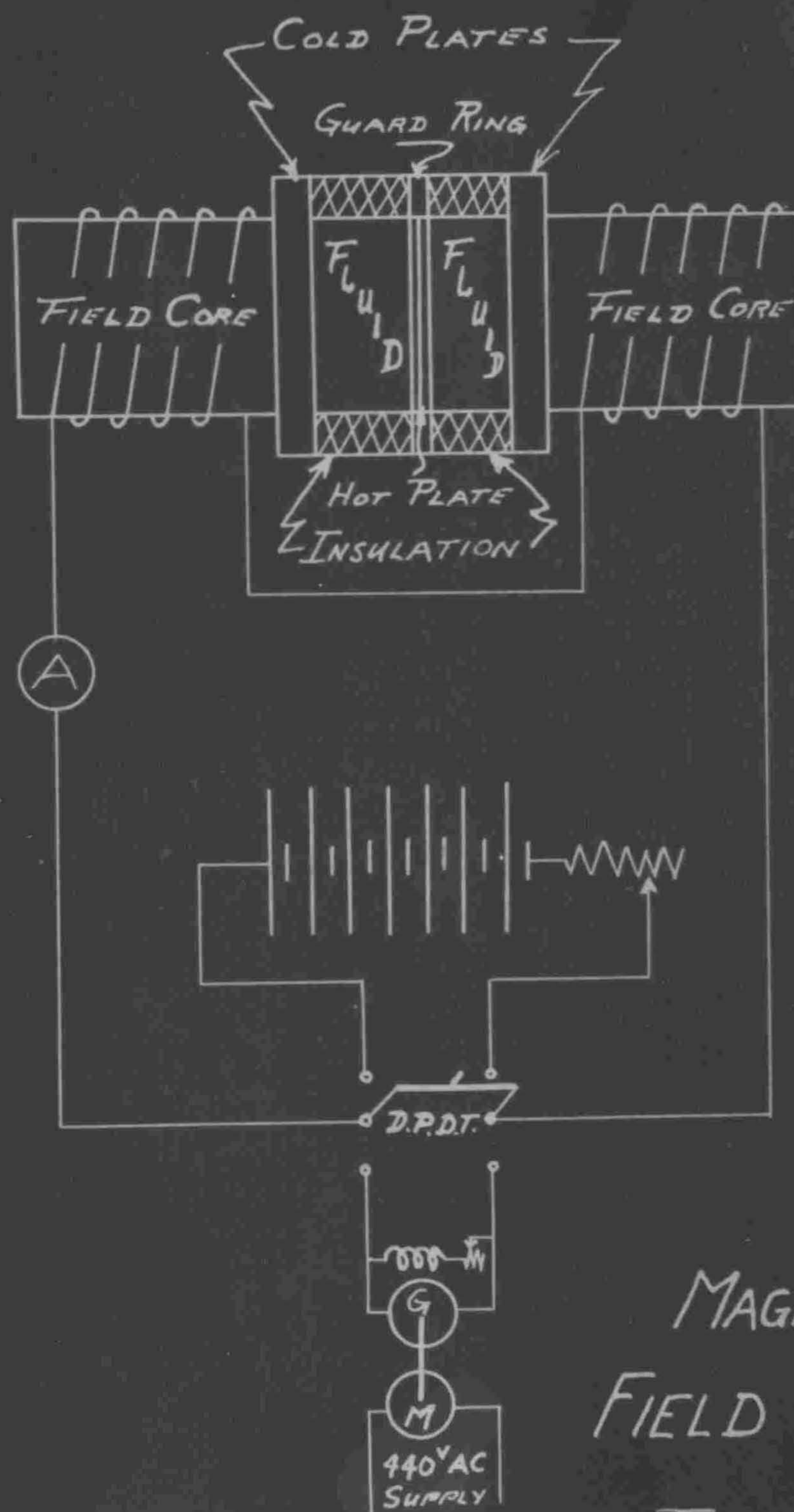
K for Runs #3 & #4 = $\frac{98.48\ I^2}{\Delta T}$

K for Runs #5,6,7,& 8 = $\frac{98.77\ I^2}{\Delta T}$

Run	Date	Time	Ave Temp Hotside	Ave Temp Coldside	Ave Temp Difference	Ave Temp (Mean)	Heat Coil (Amperes)	Amp-Turns	Coef. "K"
Run #7	4/5	1200	77.42	52.85	24.57	65.14	1.1467	4800	5.29
	4/5	1300	78.20	53.01	25.19	65.61	1.1567	4800	5.25
	4/5	1400	78.20	52.98	25.22	65.59	1.1601	4800	5.27
Run #8	4/8	1300	84.39	54.55	29.84	69.47	1.2878	5920	5.49
	4/8	1400	85.02	53.73	31.29	69.38	1.3229	5920	5.52

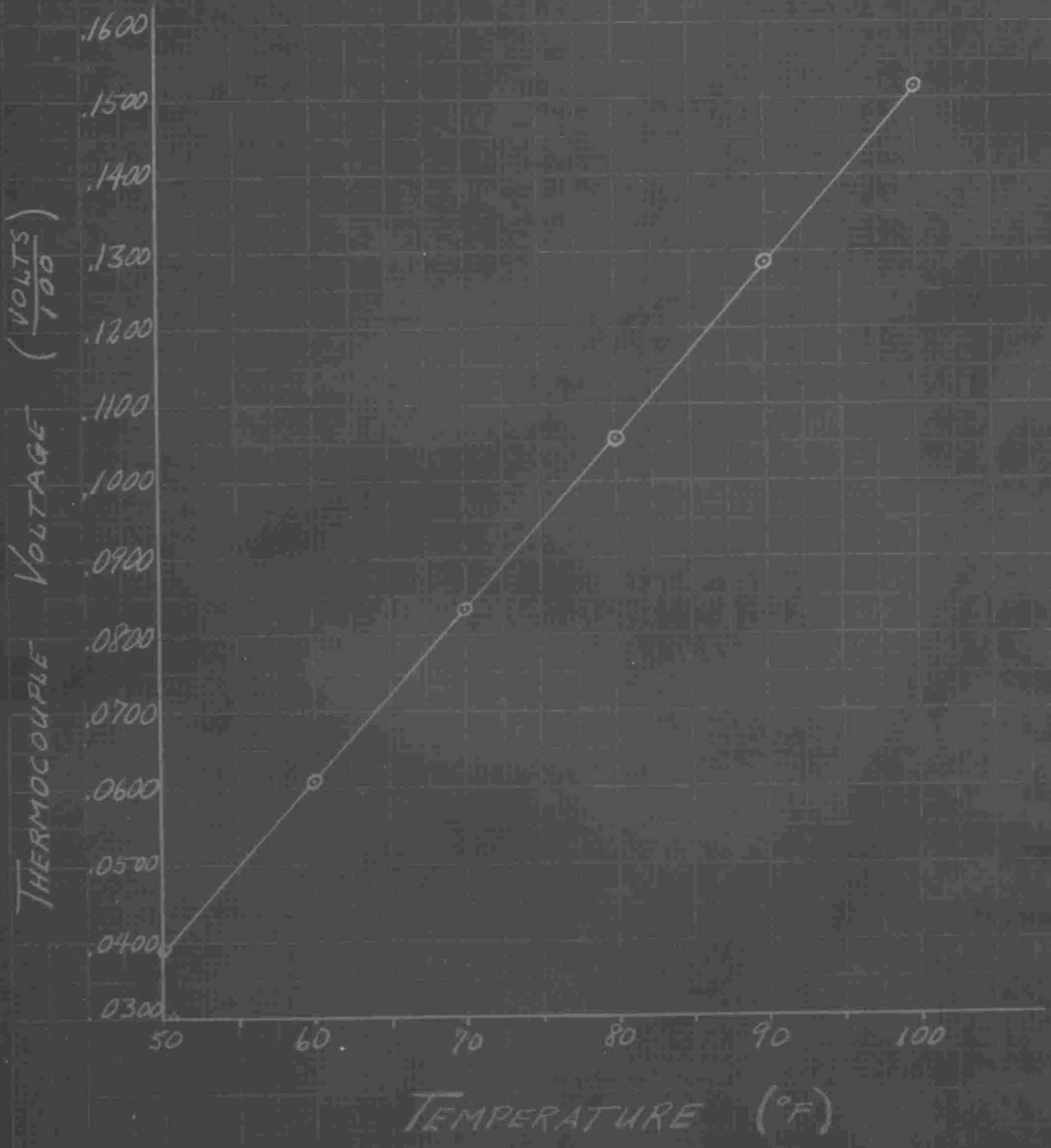


SCHEMATIC DIAGRAM — CONTROL CIRCUIT FIGURE 5



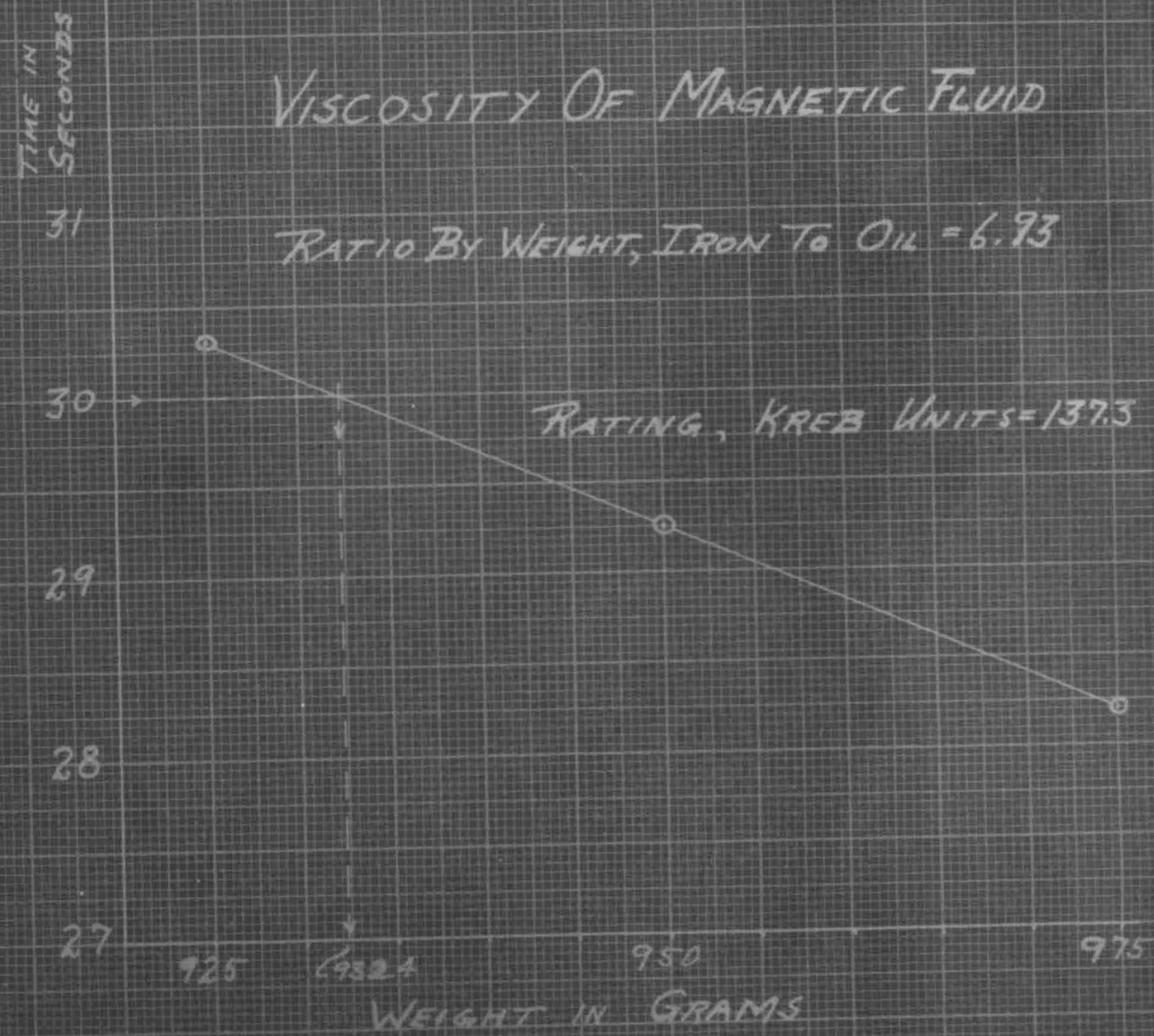
MAGNETIC FIELD CIRCUIT

FIGURE 6



CONVERSION CURVE, VOLTS/100 TO TEMPERATURE

FIGURE 7



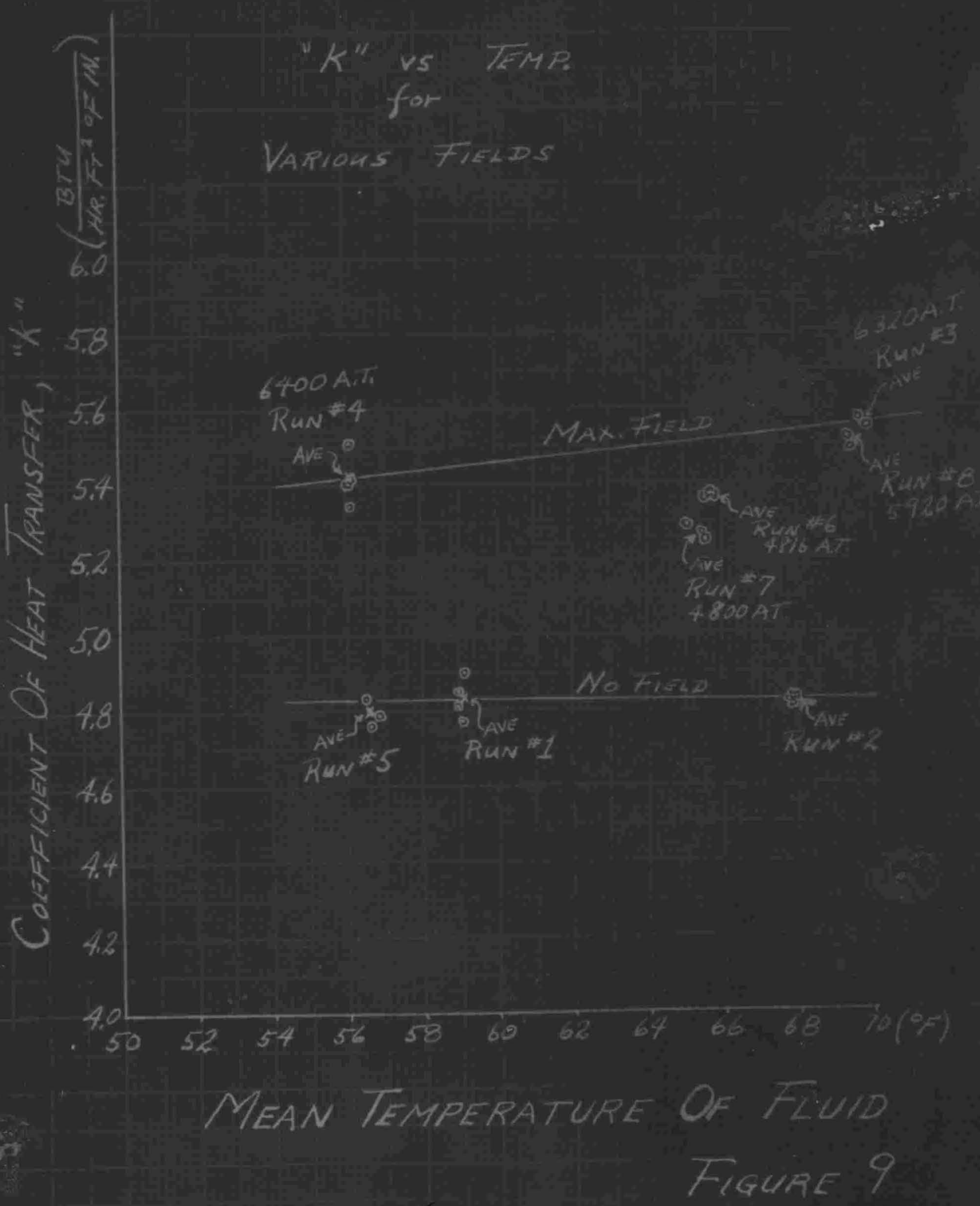
KREBB-STORMER VISCOSITY TEST

FEDERAL STANDARD STOCK

CATALOG # TT-P-141a-47

METHOD 428.1

FIGURE 8



"K" vs TEMP.
for
VARIOUS FIELDS
COEFFICIENT OF HEAT TRANSFER, "K" (BTU / HR. FT.² °F IN.)
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
4.4
4.2
4.0
50
52
54
56
58
60
62
64
66
68
70 (°F)
6400 A.T.
RUN #4
AVE
MAX. FIELD
6320 A.T.
RUN #3
AVE
AVE
RUN #8
5920 A.T.
AVE
RUN #6
4816 A.T.
AVE
RUN #7
4800 A.T.
NO FIELD
AVE
RUN #5
AVE
RUN #1
AVE
RUN #2
MEAN TEMPERATURE OF FLUID

FIGURE 9

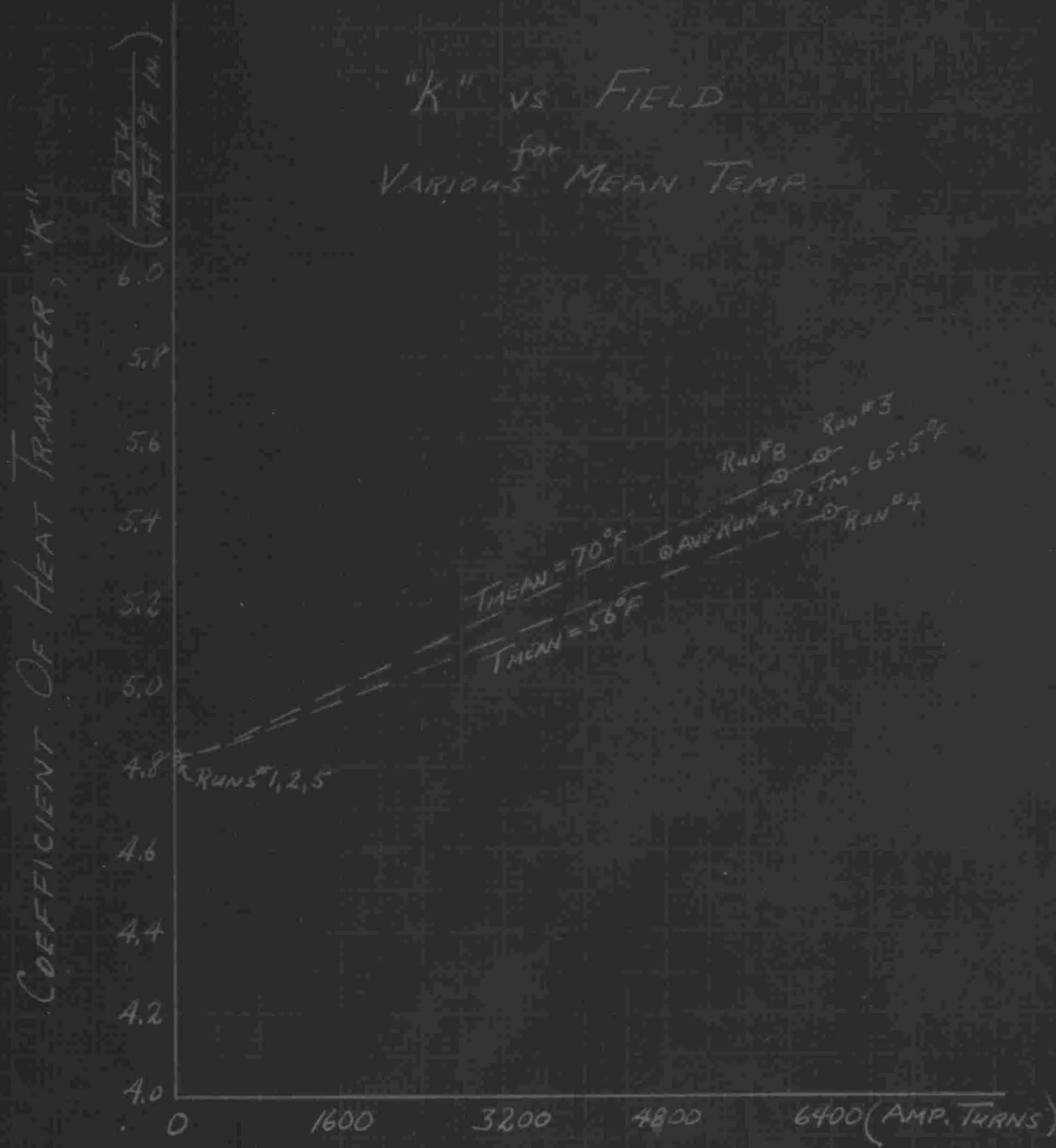

"K" VS FIELD
for
VARIOUS MEAN TEMP.
COEFFICIENT OF HEAT TRANSFER, "K" (BTU / HR FT² °F IN.)
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
4.4
4.2
4.0
0
1600
3200
4800
6400 (AMP. TURNS)
RUNS #1, 2, 5
TMEAN = 70°F
TMEAN = 56°F
RUN #8
RUN #3
AVG RUN #6+7, TM = 65.5°F
RUN #4

FIGURE 10

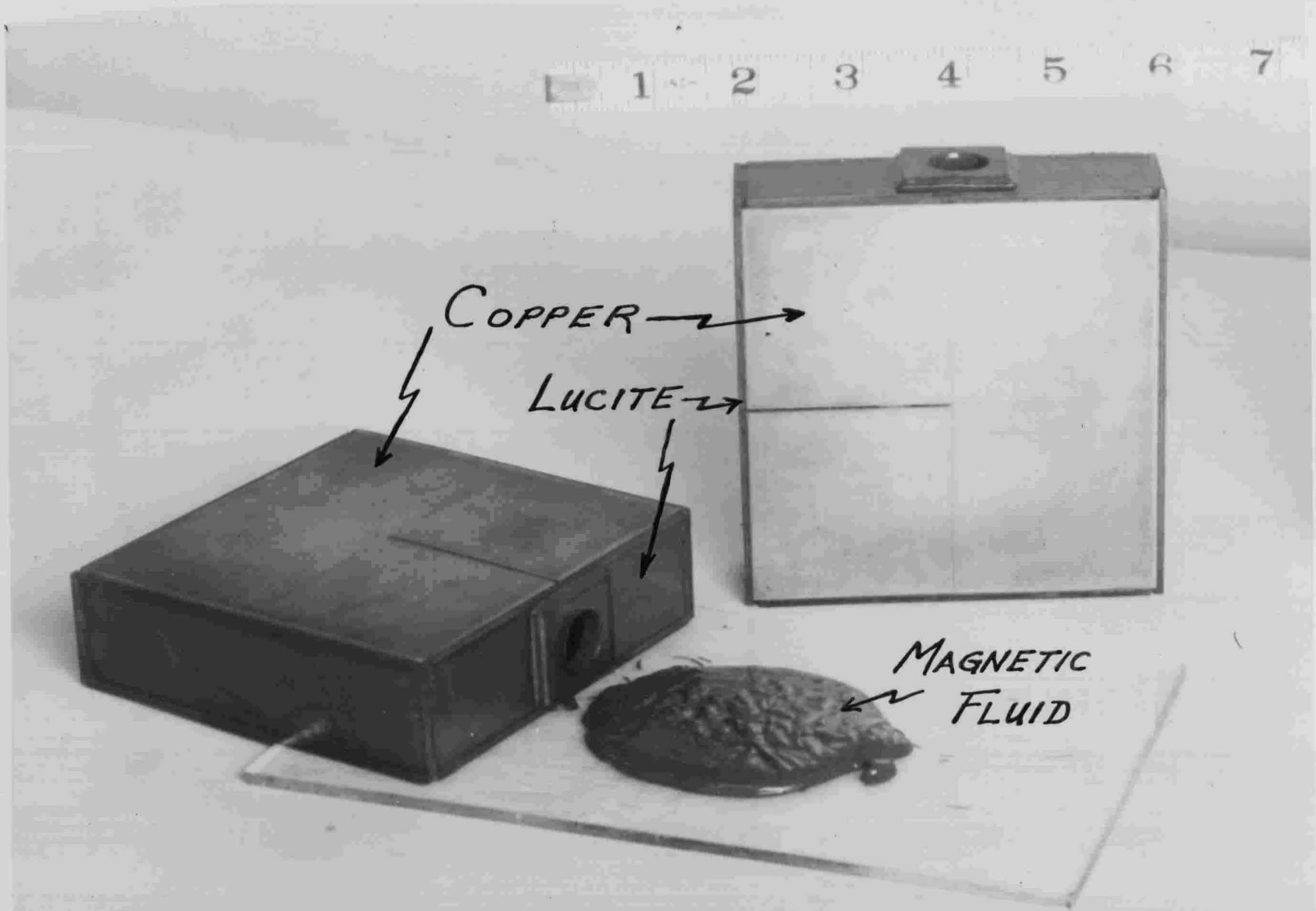


FIGURE 1

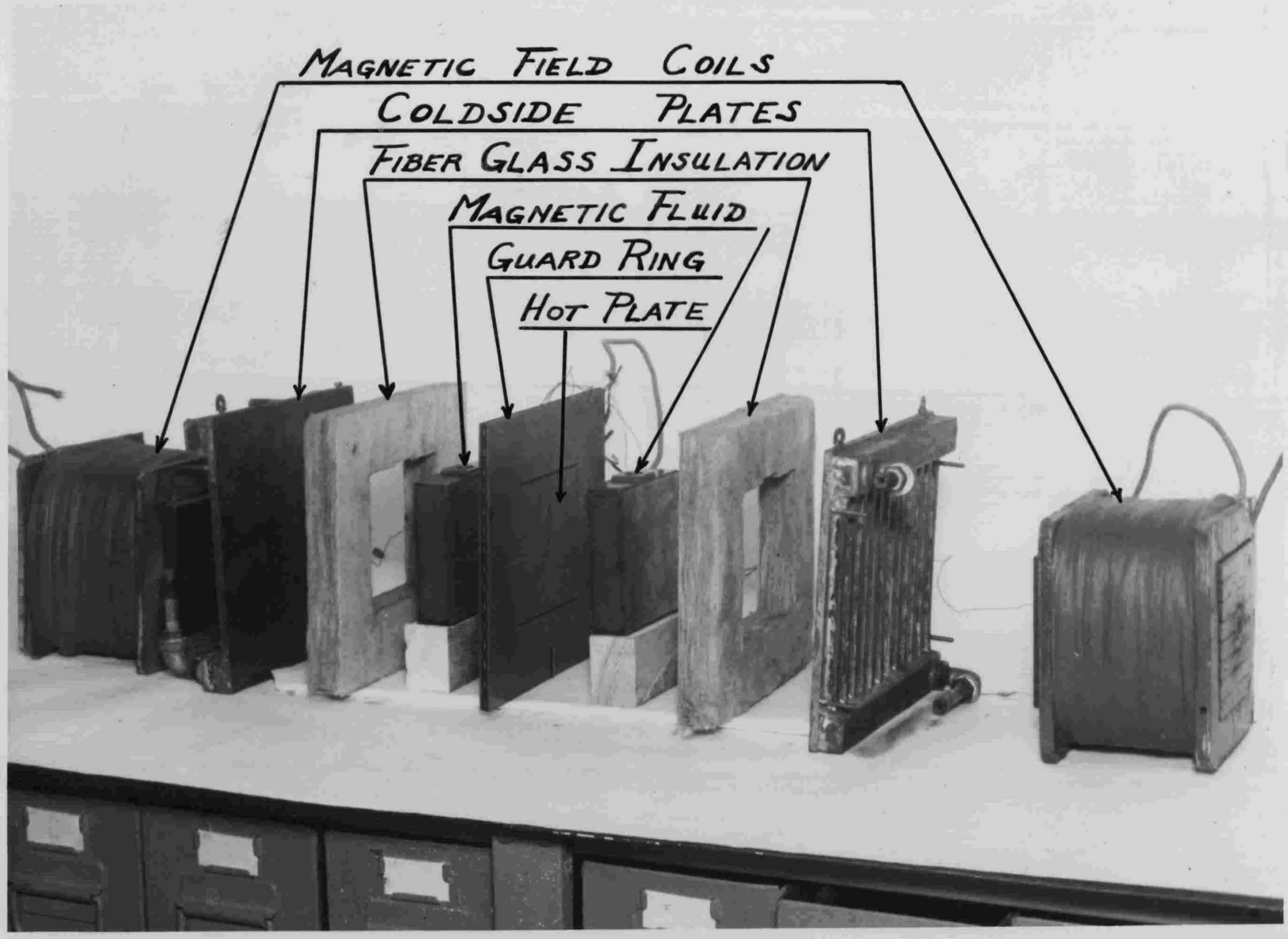

MAGNETIC FIELD COILS
COLDSIDE PLATES
FIBER GLASS INSULATION
MAGNETIC FLUID
GUARD RING
HOT PLATE

FIGURE 2

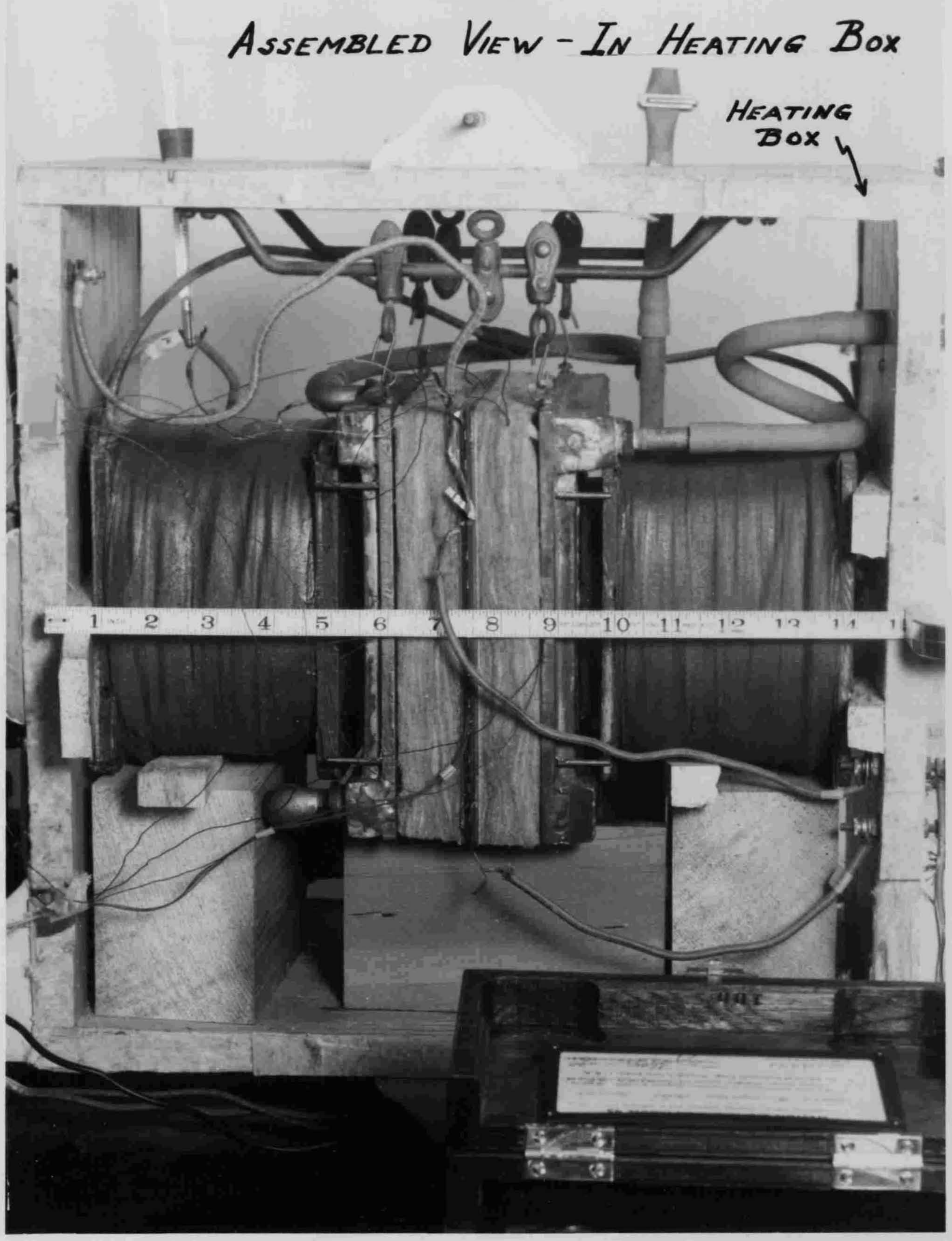


FIGURE 3

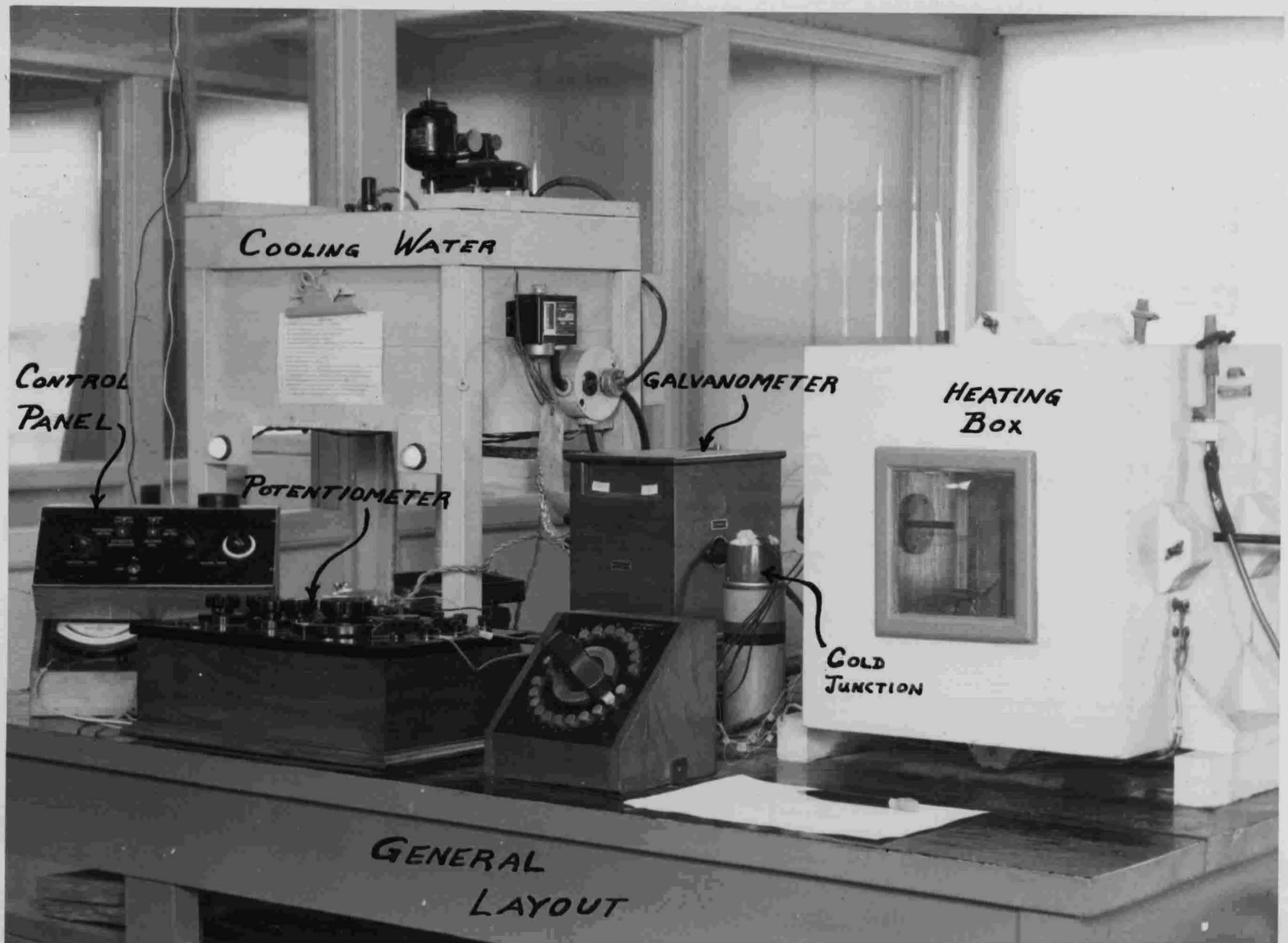

COOLING WATER
CONTROL PANEL
GALVANOMETER
HEATING BOX
POTENTIOMETER
COLD JUNCTION
GENERAL LAYOUT

FIGURE 4